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The Development of Reflexes and Reflex Tracts.

I. THE REFLEX-CIRCLE.

BY

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INTRODUCTION.

Reflexes are very important manifestations of life. The ancient definition reserved this term for the "involuntary" reactions of living matter upon acute alterations of the outer world, but the study of those processes has revealed that these limits are artificial ones which do not exist in nature. For involuntary reactions of living matter upon acute alterations of the outer world show gradual transitions into voluntary conscious reactions on the one hand,¹⁾ and into reactions upon chronic alterations in the outer world on the other hand.²⁾ These reactions upon chronic alterations are primitive forms

¹⁾ Steering a bicycle — at first a series of conscious reactions — becomes by practice more and more unconscious and thereby "involuntary".

²⁾ A certain lasting attitude can be caused by a permanent alteration of the surrounding world in the same way as it can for a moment be caused by an acute one. Hypertrophy of a muscle is seen with frequently repeated acute reflexes in consequence of a lasting alteration in the outer world.

of adaption of living individuals to the circumstances they live in, a phenomenon not yet analysed in its details but extra-ordinarily important in the differentiation of organs. The different reactions of living matter form one group of phenomena, all one in nature. In that one group no limits exist between the different forms in which those phenomena occur; only artificially we can separate such different forms and for convenience' sake give them different names, as for instance the name of "reflex" to those reactions in which conduction by means of cells plays an important part (S h e r r i n g t o n), or the name "differentiation of organs" to those reactions in which the lasting alterations of the body come to the front. But in doing so we have always to consider that these names express phenomena which mutually transit gradually and which are only quantitatively different forms of one idea i.e. a reaction of living matter.

Reactions of living matter show some characteristic differences with reactions of dead bodies. These differences seem to be the same whether we study higher animals and even humans, or the simplest one-celled organisms and whether we consider animals or plants. For instance, where in physics the law of equality of action and reaction is seen and in chemistry the constancy of a reaction however often it may have occurred, reflex-reaction in biology appears to be dependent on whether — and if so how often — the same action has exercised its influence before.

Here evidently the reacting living matter itself is changed by the former action, and so the circumstances under which the following reactions come about do not correspond to those under which the first took place. It is true that this makes the difference between the reactions in dead and living nature less, but it proves at the same time that the knowledge of living matter, of the living albumen molecules and their arrangement is necessary for an insight into the nature of a reflex.

Owing to the inequality of reflex reactions even in the case of equal actions of the outer world, it is difficult to lay down a law by which the relation of action and reaction in living nature is bound. And only such a law can reveal the unity in all the different actions of living beings.

With higher animals this relation depends in the first place on the configuration of the reflex tract, the way along which the reflex processes move from the place of the reflex action to the place of the function which will be the reflex reaction, and in order to study that relation we may ask first by what powers this reflex tract is determined.

This question touches upon the unknown primary relationship

between receptor and effector, between the organ that receives the stimulation (the action of the outer world) and a certain other organ that will function as a result of that stimulation. *Through what cause does the reflex process which has originated in and proceeds from a certain stimulus-receiving organ, choose a certain other organ towards which it will move, and which it will incite to function?*

Our experience teaches us that this is by no means an unfounded choice. The effector is always an organ that in the strictest sense of the word can *respond* to the stimulus; its action is not only a result of that irritation but very specifically alters the relation of the animal with regard to the cause of that irritation, and this *response*, according to our experience, is in the majority of cases a *useful* one. Based on calculation of chances, the chance that the stimulus out of all possible functions would just choose a useful one, would be indeed less than 50% if this connection between receptor and effector were a matter of unfounded choice.

It is just these two characteristics — the *response* and the *usefulness* — in higher animals depending on the choice of the reflex tract, which are very important qualities of the reflex itself.

Thus a clearer understanding of the origin of that tract directly gives us a deeper insight into the way in which the reflex is effectuated, and will later on make it possible perhaps to penetrate from this side into the nature of the reflex.

PRESENT STATE OF OUR KNOWLEDGE CONCERNING HODOGENESIS.

The present state of our knowledge of brain anatomy, and especially of neurogenesis, gives us the key to analyze the development of the tracts chosen by the reflex processes, and sheds some light upon the important question of the primary relationship between receptor and effector.

The tracts of the reflexes in higher animals are anatomically demonstrated by the nerve-fibres which conduct the reflex processes from the receptors to the effector, and in recent years the powers are revealed which may determine the way along which nerve-fibres grow out.

K a p p e r s¹⁾ found that the offshoots of a nerve cell — neurites

¹⁾ C. U. Ariëns Kappers. Phylogenetische Verlagerungen der motorischen Oblongatakerne; ihre Ursache and Bedeutung. „Neurol. Centralblatt“. 1907.

C. U. Ariëns Kappers. Weitere Mitteilungen über Neurobiotaxis. Die Selectivität der Zellenwanderung. Die Bedeutung synchronischer Reizverwandschaft etc. „Folia Neurobiol.“ Bd. I. 1908.

as well as dendrites — show a definite selection in their end points, in such a way that they connect that nerve cell with territories which often functioned simultaneously with that nerve cell itself, before this special anatomical correlation is established, in other words, that functional correlation precedes the anatomical correlation. He and other investigators have demonstrated this phenomenon of "neurobiotaxis" in a great number of phylogenetic and ontogenetic facts.

In a paper on the development of the cranial nerves and their central tracts, I described three laws to which the outgrowth of axis-cylinders and dendrites is bound ¹⁾. These laws could be brought under one point of view by saying that nerve fibres originate along stimulation-currents which irradiate perpendicularly from stimulated surfaces (e. g. from the skin or from amyelinated axis-cylinders) into the surrounding protoplasm. That these stimulations activate the young neuroblasts was demonstrated among others by fibre tracts which at a certain moment started to conduct a new category of stimulations. These tracts activated at that very moment a new category of neuroblasts in their neighbourhood, from which axons then grew in a perpendicular direction away from that tract.

In the ontogenetic development most of such stimulations have become engrammatic, and the outgrowth of a neuroblast seems then to be based entirely on the laws of inheritance, and to be a mnemonic repetition of the phylogenetic stimulogeneous fibrillation. The same of course holds good for the ontogenetic neurobiotactic correlation.

In 1916 Kappers drew attention to the fact that the electric phenomena in consequence of local irritation ("negative Variation") might cause galvanotropic phenomena of growth which are identical with the processes seen in the stimulogeneous outgrowth of the neurones ²⁾, and that this differentiation of a nerve cell may be a galvanotropic phenomenon in consequence of local stimulation in the neighbourhood of that cell. This explanation has the advantage of giving reasonable ground for the precocity of the development of the axon before the dendrite, the stimulo-concurrent character of the latter, and neurobiotactic selection. The electric current moves most

¹⁾ S. T. Bok. Die Entwicklung der Hirnnerven und ihrer zentralen Bahnen. Die stimulogene Fibrillation. Folia Neurobiologica 1915.

S. T. Bok. Stimulogeneous fibrillation as the cause of the structure of the nervous system. Psych. en Neurol. Bladen, Amsterdam 1915.

²⁾ C. U. Ariëns Kappers. Further contributions on neurobiotaxis No. IX. An attempt to compare the phenomena of neurobiotaxis with other phenomena of taxis and tropism. The dynamic polarisation of the neurone. Psych. en Neurol. Bladen, Amsterdam 1916.

See also Journal of Comparative Neurology Vol 27, 1917.

easily in the direction of the greatest electrolytic ionisation, and that ionisation is found in protoplasm which functions at the same time as that current occurs, i. e. in territories which function simultaneously with the growing nerve cell.

In this manner the special choice of the path of a great number of neurites and dendrites in the central nervous system was brought back to a common quality of living matter, and thereby it was revealed that the course of a nerve fibre is entirely determined by the qualities of the stimulations which activate that fibre.

Now the question is: what are the stimulations that determine the nerve fibres of a reflex arc?

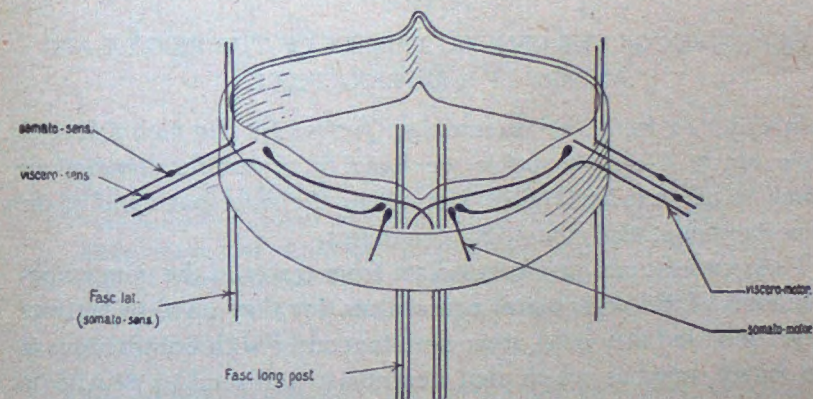


Fig. 1. A. cross-section of the rhombencephalon of a 4 days' chicken-embryo.

In the above-mentioned paper I have already demonstrated how stimulogeneous fibrillation and neurobiotaxis — i. e. galvanotropic neurogenesis of Kappers — suffice to determine the outgrowth and the configuration of the sensory and central neurones of the primitive reflex-arc, and how stimulogeneous fibrillation determines the outgrowth of the motor-cells, starting from the supposition that the skin is often stimulated in a number of segments at once, but the intestina in one segment only. On account of what stimulation and correlation, however, the neurites of the future motor cells actually reach the muscles could not yet be determined, since it was evident that the function of a central activating tract alone did not suffice for this selection. It is true that the muscle functions later on simultaneously with a motor nerve cell, for this function then is incited by the irritation of that cell, but such is only the case when the nerve-muscle connection has been already established, and thus it cannot give us an explanation of the cause of this connection. We

have therefore to look for another, not resulting but organising, cause of this synchronism.

The following hypothesis concerning this question has been given by Strasser.¹⁾ The functioning of a muscle causes an electro-negative potential in that muscle, which potential must induce a positive and a negative pole in an adjacent neuroblast. Strasser presumed that the attraction between the electro-negative muscle and the positive pole of the neuroblast was the cause of the outgrowth of the neurite out of that neuroblast. That only very few cells of the central nervous system show these offshoots, and that the cells in the immediate neighbourhood of the muscle do not show them, however, contradicts this theory of electrostatic induction.

The difficulty in finding the primary selective relationship between the muscle and the neuroblast, which is also the difficulty in finding the primary relationship between receptor and effector of the whole reflex-arc, remains unsolved in this theory.

DEDUCTION OF THE GENETIC THEORY OF THE REFLEX-ARC AS PART OF A REFLEX-CIRCLE.

In order to learn the determining factors for the motor fibre to grow out to a certain muscle we have to search for stimulations which would activate a fibre just along the same path and at the same moment as that motor fibre originates.

These stimulations have to irradiate from tracts in the very neighbourhood of the future motor neuroblasts (for they have to activate these cells) and they must occur simultaneously with contractions in the muscle towards which that neuroblast will send its neurite (in this case only the activated fibre will grow towards that muscle according to neurobiotaxis).

We shall see in the following pages that the stimulations produced by a contraction of a muscle fulfil these conditions, and give us a satisfactory genetic theory of the reflex-arc.

Muscle tissue is phylogenetically older than nerve-tissue, and it might therefore function before the nerve fibres existed²⁾. Such a

¹⁾ Strasser. Alte und neue Probleme der entwicklungsgeschichtlichen Forschung auf dem Gebiete des Nervensystems. Ergebnisse der Anatomie und Entwicklungsgeschichte I, 1892.

²⁾ It is possible that this function then was incited by stimuli which reached the muscle along that same road in protoplasm not yet differentiated, and this behaviour is even probable in the stadium just before the motor nerve fibre grew out. The plasmodesms and syncytium, however, form a reticulum without any dominating direction. Thus stimulations might reach the muscle from every direction from every point of the body, and it is not necessary that these stimulations were always the specific motor stimulations of higher animals. That the muscle could function even without "nerve-stimuli" is very probable when we consider the existence of a great number of muscle-cells without nerve-fibres in mucous membranes and in glands, and is rendered almost certain by the direct irritability of muscle-tissue and the automa-

muscle contraction always causes an alteration in the position of some parts of the body in relation to other parts or to the surroundings of the animal.

Thereby each muscle contraction caused, actualised and altered a definite group of sensory stimulations in definite receptors of the same individual.

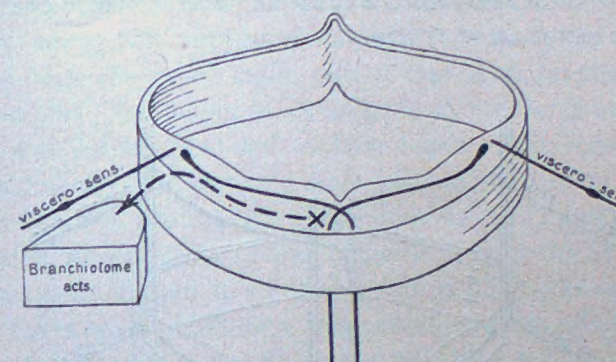


Fig. 2. Contraction of a branchiotome actualises bilateral stimuli in viscerosensory nerves in one segment. The figure shows the tracts along which these stimuli are conducted towards X, the first place they meet (= future motor cells). According to stimulogeneous fibrillation and neurobiotaxis a fibre must grow out along the dotted line (= future viscero-motor fibre).

I have already mentioned that the sensory stimulations must give rise to the known sensory and central neurones of the 4 days' chicken-embryo (fig. 1). The study of the course of these fibres shows that the stimulations which are actualised by a muscle contraction meet in the future motor cells of that muscle.

As a rule a contraction of a *visceral muscle* (derivate of a branchiotome) will actualise *bilateral viscerosensory stimulations in one segment*: e. g. a muscle of the intestinal tube alters by its contraction the lumen of that tube and thereby stimulates the mucous membrane of both sides in the level of that muscle. These stimulations are conducted by viscerosensory nerve-fibres which end in the dorsal part of the neural tube in the segment of that muscle (fig. 2). Here the second neurone originates, which crosses in the same level and turns off in the hetero-lateral fasciculus longitudinalis posterior

tism of a number of muscles (heart, vessels, experiments on isolated muscle-cells in different solutions, etc.) Although we do not know which of these incitements was the most frequent in the old phylogenetic stadia, the possibility of contraction itself without the specific motor nerve impulse of higher animals is very probable, not to say certain.

(in the medulla spinalis called fasc. long. anterior). In consequence the cells near this fasciculus longitudinalis (x in fig. 2) are the first reached by stimulations of both sides (the homolateral stimulations are irradiated by the uncrossed part of the homolateral central neurone, the heterolateral stimulations are irradiated by the crossed part of the heterolateral neurone). These cells are the future visceromotor cells. So these are stimulated by the visceral muscle-contractions before the motor nerve existed.

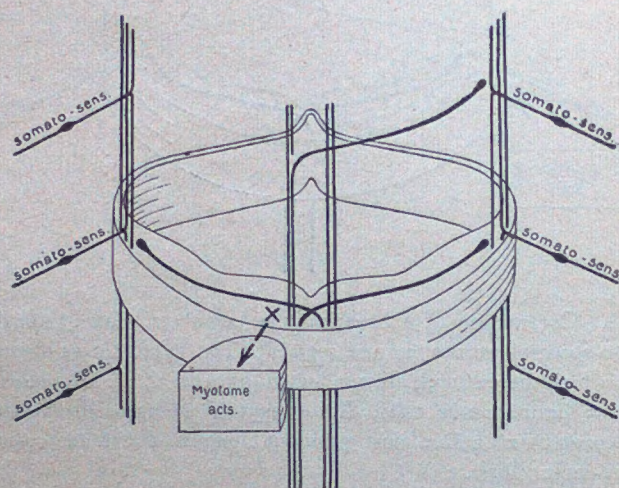


Fig. 3. Contraction of a myotome actualises bilateral stimuli in somato-sensory nerves of numerous segments. The figure shows the tracts along which these stimuli are conducted towards X, the first place they meet (= the future motor cells). According to stimulogeneous fibrillation and neurobiotaxis a fibre must grow out along the dotted line (= future somato-motor fibre).

A contraction of a *somatic muscle* (derivate of a myotome, moving the skeleton) actualises different *somato-sensory stimulations* on both sides in a number of segments, since it alters the position of the individual. Thereby it often actualises *optical stimulations* too. These somato-sensory stimulations are found to be conducted by somato-sensory fibres which dichotomise after entering the side wall of the neural tube (fig. 3) and so form two lateral longitudinal bundles. From these somato-sensory bundles all the somato-sensory stimulations, received in a number of segments, can proceed into the secondary neurones in the segment of the contracting muscle. We saw that these secondary neurones meet in the neighbourhood of the future motor cells (x in fig. 3) which thereby are stimulated by the irradiation of these somato-sensory stimulations. Optical stimulations, too, irra-

diate in these cells, for they are conducted by the optical nerve towards the cranial cells of the fasciculus longitudinalis posterior in the mesencephalon. After the optical tracts have reached the mesencephalon all stimulations which are actualised by a somatic muscle contraction thus meet in cells near the fasc. long. post., in other words, in the future somato-motor cells.

So each contraction of a muscle actualises stimulations which irradiate along the segmental cells near the homolateral fasc. long. post. (i. e. into the future motor cells of that muscle) before the motor nerve existed. According to stimulogeneous fibrillation these stimulations will incite these cells to form neurites along their path, i. e. perpendicularly upon the fasc. long. post. and (according to the law of neurobiotaxis) towards the functioning muscle. These theoretically constructed fibres (in figs. 2 and 3) appear to be wholly identical with those actually known as growing out from those cells, which occur at the moment in which these theoretically constructed fibres would grow out. For each motor fibre grew out at the very moment when the central nerve tracts were developed in such a degree that a contraction of the corresponding muscle might irritate the neuroblast of that motor fibre, viz. the visceromotors grew out after the fasc. long. post. arrived in their level, at the moment the arc-fibres of their level started to cross, the somato-motors just after the optical fibres reached the cranial part of that same fasciculus (an example of which is given in fig. 4).

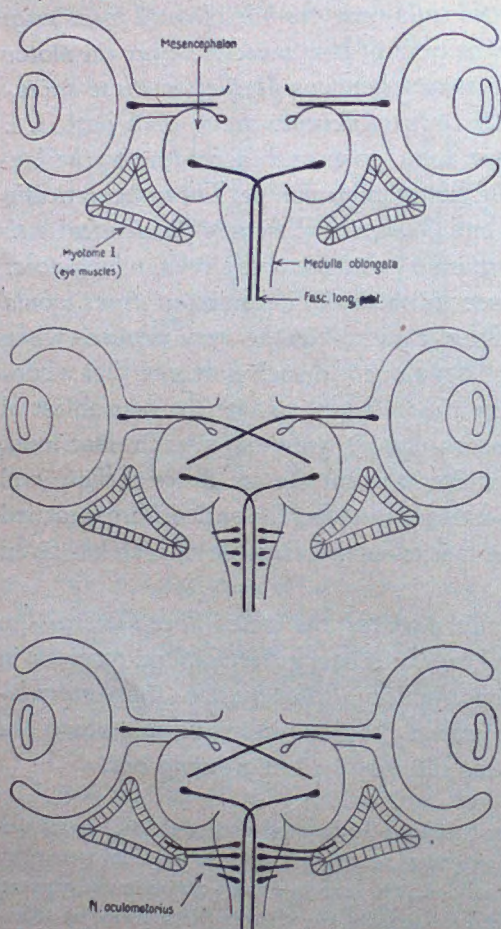
So the outgrowth and the path of the motor fibre towards the muscle is wholly determined by the sensory stimulations received in consequence of a primary contraction of that muscle: these stimulations must activate a fibre just at the same time and just along the same path along which we see the motor fibre growing out.

In order to determine the first and second neurone of the reflex-arc the supposition had to be made that the somato-sensory nerves (e.g. those of the skin) were often stimulated in a number of segments at once, the viscerosensory nerves in one segment. This supposition does agree with the determination of the motor neurone by stimulations received in consequence of muscle contractions. A somatic muscle stimulates somato-sensory nerves of numerous segments, a visceral muscle alters locally the lumen of the intestinal tube or of a blood-vessel and thereby stimulates viscerosensory nerves in one segment. So the determination of all the neurones of a motor reflex-arc can be reduced to one power, viz. to the stimulations received in consequence of contractions in the muscle, which later on will be the effector of that reflex arc.

If we now take up again the question of the determining forces of the reflex tract in a more general way, we can start from the fact found in the former part that stimulations actualised in a number of

receptors by a primary muscle contraction will activate fibres that are identical with the nerve fibres of the motor reflex-arc really found in vertebrates.

This view does not start from the function of the receptor, but just from the action of the effector, which sounds strange at first, since we are accustomed to look upon the action of the effector as a result only of irritation in the receptor. According to the above-mentioned



72 hours incubation.
The fasc. long. post. has existed for 20 hours. The opticus fibres grow out.

79 hours incubation.
The opticus fibres have reached the mesencephalic nuclei of the fasc. long. post. Perpendicularly upon this tract the oculomotorius fibres grow out (stimulogeneous fibrillation).

84 hours incubation.
The oculomotorius fibres, which are activated by optical stimuli, grow towards muscles which actualise optical stimulations (neurobiotaxis).

Fig. 4. The N. oculomotorius grows out when the stimuli which are actualised by myotome I (alterations of the retina-images) reach its neuroblasts. (Schematic figures after three chicken-embryos which I described in *Folia Neurobiologica* 1915).

facts, however, the condition of the involuntary reflex in higher vertebrates — upon which that ancient view is based — has to be considered as a secondary condition, the evolution of which closely depends upon the development of the reflexes themselves, while the primary condition is a totally different one, the reverse of it.

Before the nerve fibre connection between receptor and effector occurred a similar reflex path probably already existed, but not yet differentiated in neurones. This, however, is no principal difference, and in order to understand the origin of that reflex-tract we must go further back, namely to the stadium in which the reflex had not yet taken this tract.

The effector then functioned upon a stimulus which reached it by a different path. Whether that was also a reflex process limited to a constant or a varying tract, or whether that function came about by direct mechanical or chemical stimulations is of no importance to our consideration. So much is certain, that every time the effector functioned — incited thereto by any cause whatever — this function had a very definite effect, the character of which chiefly depended on the effector and not only upon the stimulation which incited it to function.

This effect caused, actualised and altered stimulations in very definite receptors of the individual itself. These stimulations spread over the individual, and in doing so they tend to approach each other according to the law of neurobiotaxis (are associated as simultaneous stimulations), and since they coincide with a state of stimulation in the effector (contractile substance or gland) they will turn to that simultaneously irritated, ionised organ too, according to that same law (they are also associated with that effector).

This process always takes place with every function of the effector and, according to stimulogeneous fibrillation, nerve-fibres will soon grow out along the path of these often repeated stimulations. Thus the nerve-fibres from definite receptors to that definite effector will lead to the effect — and this of great importance to the individual — that now other stimulations received in the same receptor will likewise take that tract, and that also their energy will arrive at the same effector. In consequence of this, "the tables are turned", and the function of the effector becomes a "result" of irritation in the same receptors, the stimulations of which it used to actualise before, and the reflex as such has arisen.

At first the effector-function formed the action, and the stimulation of certain receptors of it the reaction; inversely, the irritation of these receptors has now become the action of which the effector-function is the reaction.

This view of the origin of the reflex-tract extends our attention over a greater area than the reflex-arc itself, the path of the receptor to the effector. The reflex-arc becomes part of a "reflex-circle" by the thesis that the effector-function resulted in the irritation of the

receptor of that same reflex-arc (for exceptions by secondary changes in higher developed reflexes, see below).

This conception of the "reflex-circle" teaches us that the reflex-arc is the path of the stimulations received in consequence of a function of the individual itself. According to the law of neurobiotaxis these stimulations must move every time from their receptors to the functioning organ (synchronism of functions). The nerve-fibres growing out along this path according to stimulogeneous fibrillation will then also conduct the other stimulations received by those receptors towards that same effector.

PSYCHOLOGICAL, ANATOMICAL AND PHYSIOLOGICAL EVIDENCE.

Considering this conclusion, we must first admit that it is a logically necessary consequence of the two most elementary ones of our present ideas about psychology, of the thesis of association of simultaneous or successive stimulations and of the thesis of memory. Accepting the correctness of those two ideas, then this way of originating of the reflex-tract is a necessary result of it. The many stimulations arisen, actualised or altered in consequence of an effector function must then associate as simultaneous stimulations, and not only will they associate together but also with that effector function itself. The reflex path must then, in short, originate in this way as an intense engram of the association of the effect of a function with that function itself, being simultaneous phenomena.

Although this view consequently agrees with the present state of psychology, any indication of its correctness on an anatomical or physiological basis will be welcome.

In the preceding pages we saw that the development of reflex neurones (especially of the motor neurone) furnished anatomical arguments in favour of the view here defended concerning the reflex circle. The most important of these arguments were the following:

1. Each motor fibre grows out at the very moment when the stimulations actualised by contractions of its future muscle are conducted towards its future nerve-cells (an example of which is given in fig. 4).
2. Each motor fibre grows out at the place where the stimulations actualised by contractions of its future muscle meet (cf. fig. 2 and 3).
3. According to two general laws of brain anatomy (neurobiotaxis and stimulogeneous fibrillation) the stimulations actualised by a muscle contraction must differentiate neurones which are identical with the known motor neurones of that muscle (and which originate at the same moment as these motor neurones originate).

What is the argumentative force of these anatomical data?

We know that, if the stimulations which are actualised by muscle contractions differentiated neurones, these neurones must be identical with the motor neurones of that muscle actually present later on (3). It must be termed highly improbable that more than one general influence existed which could build just the same very peculiarly arranged neurones, and this makes it highly probable that the motor neurones actually are differentiated by the stimulations actualised by muscle contractions.

This could only be rendered certain if experiments could demonstrate this cell differentiation, which is impossible, however, in the present state of experimental biology since this differentiation is a phylogenetic one. If, therefore, we want more arguments in favour of our hypothesis we can only search for cases in which the hypothetical causes differ: if these causes include the true ones the differentiation in those cases must occur in different ways. This, too, was realised in the preceding pages, for it was stated there that when the said stimulations meet at another time or at another place the corresponding neurone originates at that other time (1) or at that other place (2), and so nature itself renders some experimental proofs too in favour of the theory of the reflex circle.

In reflex physiology we meet with some peculiarities which are in favour of this opinion. However, because there is no systematic comparing phylogenetic reflex physiology, physiologic facts speak less decidedly in a definite sense in questions concerning the successional development of reflexes. On the other hand, they often elucidate existing relations in a clear way.

In the first place, we may cite the fact that the same stimulus applied in different intensity may cause opposite reactions. I have specially in view here the escape reflexes with weak stimulations, and the defence reflexes in the case of stronger ones. The simplest example of this is the touch on the sole of the hanging foot. If this touch be gentle, we see a flexion of the leg by which the sole is lifted and withdrawn from the touch; if the touch be strong, a powerful stretching is noticeable, which pushes away the object with which the sole was touched.

Apart from the possibility that this phenomenon may later on be explained starting from the receptor — as different stimulations are offered to it — we can already with our present knowledge derive it from a general rule when starting from the effector. Powerful stretching of the leg generally causes strong pressure against the sole. According to the reflex-circle idea therefore, a strong pressure

later on will incite a stretching-movement. Flexion on the contrary, on leaving the ground generally gives a weak sole-stimulus, and therefore flexion will be evoked by a weak touch of the sole. Evidently the result of the reflex-stimulus is determined by the question, by what function of the individual itself that same stimulus can be actualised in (nearly) the same intensity.

I might mention still another physiological fact. Studying the scratch-reflex, Sherrington¹⁾ established the fact that the afferent tract of a reflex is a private one, a path which belongs to that reflex only, and this one reflex has a number of such private afferent tracts.

Those numerous private afferent fibres, originating in different receptors have only in common, that they evoke the same function in the same effector and we know that that function is able to build these fibres. It is very probable therefore that their existence is really founded upon that only quality they have in common, upon the function of the effector, as it is presumed in the theory of the reflex-circle.

In favour of this conception is also the fact that the afferent fibres of the scratch-reflex occur everywhere in the whole area of the skin that can be touched by a movement of the leg, and they do not appear anywhere else in a region that cannot be reached by a movement of that leg. So here the reflex-circle gives the positive as well as the negative determinatives of the reflex-tracts.

A third physiologic consideration is the following.

The greatest number of reflexes demonstrates the primitive relation of the reflex-circle: the effector by its function stimulating the receptor of that same reflex. A muscle contraction causes stimulations in the tendon; inversely, stimulation of that tendon may cause that muscle contraction (tendon-reflex). Numerous muscles which activate or cause stimulation in constant parts of the skin are put in action by stimulation of that same part of the skin (skin-reflexes, defence and escape-reflexes, scratch-reflex and others). The same is seen in muscles the contractions of which give rise to irritations of mucous membranes (movements of the intestinal tube, pharynx-reflex, swallow, cough, sneeze-reflexes, etc.) Secretion of a gland by the fluids produced irritates the mucous membrane round the mouth of its duct; stimulation of that area of the mucous membrane causes a secretion in that gland. The number of examples of this very frequently seen phenomenon might be thus enlarged without any difficulty.

¹⁾ C. S. Sherrington. The integrative action of the Nervous System. (Constable, London, 1910).

Not all reflexes, however, demonstrate this primitive reflex-circle relation so clearly, but the phylogenetic development of these reflexes being unknown this does not prove that they have not originated as "circle-reflexes". The character of a reflex may alter afterwards by change of circumstances, f. i. a change in the form of the body (after the reflex path has been fixed in nerve-fibres) preventing the effector from giving rise to stimulations of its receptor as it did before, an example of which is given by the cremaster-reflex.

Though some reflexes are not circle-reflexes it is therefore possible that even these reflexes too have originated as circle reflexes. Extensive comparative reflex-physiologic researches will be necessary to teach whether the reflex-circle is the *only* manner in which reflexes originate (cf. page 299) So much is certain, that although physiologic data in general — as I explained above — can give us no proof concerning the causes of the development of reflexes, they in no way contradict the view of the reflex-circle expressed here but are in striking accordance with it and often point very decidedly in this direction.

So the theory of the reflex-circle, deduced from brain-anatomy and being a natural corollary of psychology (of association of simultaneous stimulations and of memory) finds ample confirmation in the physiology of the reflexes, as revealed by Sherrington and others.

THE CHARACTERISTICS OF THE REFLECTORY RESPONSE.

After having thus deduced the principle of the reflex-circle, and having tested it on account of our present knowledge of reflexes, we may ask in how far this principle sheds light upon the qualities of the reflex.

In the introduction it was presumed that a better understanding of the determining causes of the reflex-tracts might throw some light on the question as to why reflex-reaction is generally a *response* to its reflex-stimulus, and why this response is so often *useful* to the individual. The determining powers of the reflex-tracts, contained in the idea of reflex-circle, are, so to say, forced upon us when studying the embryonic nervous system, and now the question arises as to whether the action of these powers agrees with the usefulness of reflexes.

That the reflex-reaction, and therefore the effector of a certain reflex, is not a haphazard one, but that the function of the effector *responds* to the reflex stimulus — or more precisely stated, the

reaction varies the relation of the animal with regard to the reflex-stimulus — undoubtedly finds its chief cause in the fact that the motor reflex-arc is part of a reflex-circle.

The reflex-tract being the path of the stimulations which are caused, actualised or altered by the future reflex-reaction, this reflex-reaction will be reflectorically caused by a stimulus, of which it causes, actualises or alters the perception. So the reflex-reaction and its stimulus in consequence of the reflex circle are related to the same receptor. On a visual stimulation the animal must react with a movement which alters the visual stimulations, on a touch stimulus in such a way that it actualises sensory stimulations in the same part of the skin, in other words, so that the attitude very specifically changes with regard to the stimulus given. *Thus the reflex-reaction must alter the perception of the reflex-stimulus; in other words, it must very specifically alter the relation of the animal towards that special stimulus, it must "respond" to that stimulus.*

Thereby the reflex circle not only gives us the determining powers of the reflex-tract, it also gives us an answer to the question as to how the reflex-reaction is wont to be a response to the reflex-stimulus.

In the second place we know that the reflex-reactions are in most cases *useful* to the individual. Although it is unnecessary to say that we cannot give an account of a criterium whether a certain change is useful or not to the individual, we may observe that a reflex is not always useful. In choosing from the many examples generally known of useless reactions, we may mention the very striking ones of a moth which flies into a flame and of the knock-reflex of Goltz, which both result in death. So the usefulness is not necessarily an inherent quality of reflexes, but we get the impression that in the nature of the reflex something is hidden which enhances the chance that of all the possible functions of the individual one has been chosen which is useful as regards the reflex-stimulus.

Does the theory of the reflex-circle reveal a similar factor which increases the chance of the usefulness of the reflex-reaction, and is this eventual factor able to improve it sufficiently as to give us the familiar conditions, in other words, is it the only factor which enhances the usefulness?

According to the reflex-circle, reflex-reaction is a function that actualises and alters the perception of the stimulus. It is clear that a reaction which does not alter the relation of the animal with regard to the stimulus cannot bear any relation to, nor be a specific useful one to that stimulus, for only when the influence of that stimulus has been changed can we ask whether that change is useful or not. Therefore

only when the reflex-reaction alters that relation has it a chance of being a specific useful one. In that same case, however, the chance of a specific hurtful reaction increases. In numerous cases one sensory stimulus may be caused by more than one function, and inversely that one stimulus — according to the reflex-circle — will be able to evoke a number of reactions. All these reactions alter the influence of that reflex-stimulus, but in different ways. It is therefore possible that the one way may be useful and the other detrimental, and in order to find out whether the altering of the influence of the stimulus is on the whole beneficial to the animal, we have to compare the possibilities caused by those different alterations.

The perception of a stimulus is strengthened or weakened by the reflex-reaction.

In the case of weakening of the stimulus its consequences upon the animal are avoided or diminished (cf. avoiding reflexes). If strengthening of the perception always increased these consequences the fact that the reflex-reaction specially must alter that perception would be quite indifferent as to the usefulness. This is, however, not the case, since strengthening of the perception often results in an *opposing* of the stimulus, by which the consequences of that stimulus upon the animal are also diminished instead of increased.

The behaviour of living organisms shows many examples of this opposing phenomenon in strengthening the reflex-stimulus. With the defence-reflex, for instance, the perception of the offered touch-stimulus is heightened by the counter-pressure evoked, and this same counter-pressure pulls away the touching object. Here the principle of pressure and counter-pressure *heightens* the perception of the stimulus, but at the same time *opposes* its consequences. With the scratch-reflex the stimulation of a skin nerve is strengthened by the reflex-reaction in another way. Here the animal itself causes a stimulus in the same nerve by touching the skin with a part of its own body, in this case with its leg. Thereby the other body which stimulated that nerve is pushed away, and by this mode of strengthening the perception the stimulating power is also opposed. When, in the third place, the perception of a stimulus is strengthened by a movement which itself is of no use to the animal, it is possible that the stimulus — which by this first movement has grown stronger — evokes more reflex-reactions, some of which may result in avoiding or opposing it in a manner as described above (e. g. a scratch-reflex after the animal wounded itself in consequence of a defence-reflex evoked by a sharp object). With higher animals this strengthening of the perception of a stimulus, by which other useful reflex reactions are made

possible, is seen very often (e. g. a movement of the eyes in the direction of a movement in the outer world, as an example of the many adjusting reflexes of sense-organs).

Strengthening of the perception-possibilities, however, happens only in some exceptional cases to be dangerous and even dramatic, e.g. when the stimulus is a detrimental one and when its strengthening by a first reflex does not evoke other reflex reactions. This possibility is realised, for instance, by a moth which flies into a flame. Here we see that the theory of the reflex-circle not only prescribes the known useful reactions, but that it also determines the few dramatic, detrimental reactions which are seen in living nature.

Thus strengthening of the perception of a stimulus often results in opposing that stimulus, and thereby strengthening too often diminishes the consequences of alterations in the outer world.

The reflex reaction according to the reflex circle must weaken or strengthen the perception of the reflex stimulus. In the first case the consequences of that stimulus upon the animal are always diminished by *avoiding* it, and in the second case these consequences are very often diminished by *opposing* the stimulus, in other words the reflex-circle determines that the reflex reaction in the majority of cases diminishes the influence of the reflex-stimulus. The great number of hurtful reactions in face of the few actions which without co-operation of the animal are useful in themselves, renders this a useful phenomenon, leading to an avoidance of these frequently hurtful influences, or to a defence, to a state of war against them.

The reflex circle therefore augments the chance of a useful reaction by excluding indifferent reactions: thereby each reflex reaction affords a chance to escape the so frequently detrimental influences of the outer world, or to wage war against them.

With the increasing development of the reflexes (and this development is always far in advance of its anatomic manifestations, since histology only demonstrates invariable reflex-tracts with intense "Bahnung") the reflex-circle superposed on a number of primary reflexes will increasingly lead to the choice of response always more in accordance with the surroundings and thus enlarge the chance of its usefulness. Those superposed reflexes may give the preference to the more useful out of the two possible opposite primary reflexes, by which preference the chosen (most useful) one will be differentiated in neurones.

Whether this influence is sufficient to explain the great chance of a useful reaction which we can state in the animal kingdom, is a question to which no answer is possible in the present state of brain biology for we cannot estimate even approximately the influence and the

complication of the superposed reflexes, which in the animal studied are not visible in neurones yet.

I am inclined to believe that such is not the case, and that more influences must be considered here to explain why some specific useful influences are not opposed nor avoided but promoted.

In order to get a definite opinion about this important question it would be necessary among other things to examine and consider in their entire organisation older stadia of vertebrate brains than I could study. From this we might form an opinion about the nature of those superposed reflexes. We might then get an insight into the laws by which these "higher" reflexes come into existence, how they act upon each other (weakening and promoting), and if reflex-stimuli can perhaps pass over to other reflex-circles, by which new reflexes without circle might then originate.

And only then will it be possible to give an answer to the question as to whether the principle of the reflex-circle affords a sufficient shifting of chances in the direction of greater usefulness of the reflex, to render the supposition of other influences in that sense unnecessary.

A reflex-theory which starts from the fact that a reflex is useful is the psychological reflex-theory of Straub, who explained in a very brilliant paper¹⁾ that the analogue of our consciousness in lower organisms will oppose their useless actions and promote the useful ones in the manner as happens in the case of our inclinations and dislikes, as Jennings did in his theory of "trial and error". Only useful impulses by repetition would become automatically "reflectory".

This view, in my opinion, forms a complete logical system, and thus there only remains the analysis of the manner in which what Straub calls primitive consciousness tends to usefulness.

However great the difference may seem to be in their way of explaining between this psychological theory and that of the reflex-circle, their starting-point and their opinions about the real development of a reflex are in principle alike. Both start from one or other casual action of the individual itself. Both see the reflex-process taking more and more strongly marked paths and steadily becoming less accessible to the influence of other reflexes ("growing more and more unconscious or automatic", "growing more and more stimulus-generously fibrillated").

Starting from a casual action of the individual, the theory of the reflex-circle teaches us, however, how reflex-tracts must originate in consequence of that action, and by which tracts that action can afterwards be incited by those alterations of the surroundings in regard to which it may be useful. Starting from that same casual

¹⁾ M. Straub. Over den invloed van het bewustzijn bij het ontstaan en voortbestaan van reflexen. Geneeskundige Bladen voor Kliniek en Laboratorium. 1915. Bohn, Haarlem.

"not yet efficient" action, Straub emphasises the usefulness of psychic control. So the reflex-circle concerns in the first place the origin of the reflex — being already a useful phenomenon — and the theory of Straub chiefly concerns the question as to whether an existing reflex is promoted or counteracted (by superposed reflexes?).

It is impossible as yet to state whether these two theories — which are both a description of what happens in nature, and neither of which excludes the other — are different factors which complete each other or whether they are different descriptions of one factor. In the latter case the immanent usefulness of the reflex would be totally based upon the identity of the reflex-stimulus with one of the stimulations, actualised by the reflex-reaction; in the former case the usefulness of that same identity would be, moreover, enlarged by a second choice, to which we cannot give another name than a sort of psychical choice and the rules for which we do not yet know.

However this may be, in what we circumscribe as consciousness we may undoubtedly see an influence which helps to augment the usefulness of the reflex-reactions. Whether this is a second influence, or whether it perhaps will prove to be a form of the first, is a question the answer to which we must leave to the future.

So the theory of the reflex-circle not only reveals to us the determining powers of the reflex-tract, but it also includes the cause of the fact why the reflex-reaction alters the relation of the animal towards the reflex-stimulus, i. e. why it "responds" to that stimulus by altering its influence. And thereby the chance of a useful reaction is increased, since indifferent reactions are excluded, for thus each reaction has a chance to avoid or to oppose the so frequently detrimental influences of the surroundings.

In a following paper we shall see how this same principle teaches us a primary law to which action and reaction in living nature is bound, by which law it will be possible to get a clearer insight into the unity of biological and physical phenomena.

The circular course of the processes in the reflex-circle gives rise to another consideration.

That the processes of our mind are closely connected with reflex processes is not only probable by reason of the great resemblance between the substratum of our mind and that of the reflexes, but is demonstrated in nearly every chapter of brain biology, as is convincingly described, among others, by Pawlow and Straub.

Those processes of the mind are not linked with the part of the reflex-circle that lies outside the reflex-arc. That part is of course merely of a mechanico-chemical nature: the action of the effector causes by pressure-changes, sound-waves, light-changes, shiftings of the chemical equilibrium and similar processes the stimuli which irritate the animal. In truth even the immediate causes of those stimuli belong to that

action itself. They form in this action that portion which the individual experiences of that action by means of its receptors.

So what we understand by processes of the mind is related to that part of the reflex-circle which is situated between receptor and effector, upon the reflex-arc itself, and this reflex-arc may be considered to be an association of the sensory stimuli received in consequence of an action of its own with that action itself (association based upon synchronism). So that is an association of two phenomena, one in nature, viz. the action of the individual. The first phenomenon is that action, perceived by different receptors, the other phenomenon is that action in its very origin, viz. the functioning organ.

So our mind, according to the view of the reflex-circle, is closely connected with mutual associations of different expressions of the same reality. This quite agrees with the fact that we subjectively feel a strong desire to understand the one reality of which we see such different expressions, the connection of which we do not understand yet. We desire to learn to see them — if only with the eye of our mind — as one grand unity, a desire which can be traced in the nucleus of many important philosophies, with some even in words which remind us in many ways of the biological ideas described above.

SUMMARY.

The relation between action and reaction in living nature depends with higher animals in the first place upon the configuration of the reflex-tract, the path along which the influence of an action of the surrounding world — called reflex-stimulus — moves from its receptor towards the effector, i. e. towards the organ the function of which will be the reflex-reaction. Therefore the question arises, by what influences the configuration of this reflex-tract is determined.

It has been revealed that nerve-fibres connect their nerve-cell with territories which often functioned simultaneously with that cell itself (neurobiotaxis of Kappers). In the second place we know that a cell becomes neuroblast when stimuli repeatedly pass through it. Then fibres grow out of that cell along the path of these stimulations (stimulogeneous fibrillation, perhaps a phenomenon of galvanotropism). By these two laws the stimulations which "activate" a nerve-fibre wholly determine the future course of that fibre.

In a former paper I demonstrated that the first and second neurones in chicken-embryos are determined by these two laws, if we start from the supposition that the skin is generally stimulated in a number of segments at once and the mucous membranes of the viscera in one segment. By these stimulations also the outgrowth of the motor neuroblasts is determined. That the neurites of these cells reach muscles was not determined by those stimulations, however, for it was not yet clear by what influence the future motor-cells were often stimulated simultaneously with the muscle before the motor-nerve existed.

In order to learn the determining factors for the motor fibre to grow out to a certain muscle, we have to search for stimulations which would activate a fibre just along the same path and at the same moment as that motor fibre originates.

Each contraction of a muscle causes, actualises and alters stimulations in definite receptors of the individual itself (a somatic one generally in somato-sensorial nerves of numerous segments, a visceral one in the viscerosensorial nerves of one segment). The study of the course of these stimuli along the first and second neurones teaches us that they meet in the cells which will later on innervate that muscle (fig. 2 and 3). Thereby they must activate a fibre out of these cells, which fibre according to the law of neurobiotaxis must grow towards that functioning (= simultaneously stimulated) muscle. This fibre is wholly identical with the real motor-fibre which actually grows out at the very moment the first and second neurones are able to conduct towards their cells the stimulations actualised by a contraction of the corresponding muscle (fig. 4).

So the primitive motor reflex-arc of chicken-embryos is determined by:

- I. the occurrence of stimulations in consequence of an action of its own;
- II. the outgrowth of nerve-fibres along the path of repeated stimuli currents (stimulogeneous fibrillation);
- III. the inclination of nerve-fibres to grow towards simultaneously stimulated territories (neurobiotaxis).

So the reflex-arc is the path along which the stimulations received in consequence of a function of its own must move from their receptors to the functioning organ.

This theory of the "reflex-circle", which is based upon anatomy, is a logically necessary consequence of psychology: the reflex-tract must have originated in this way as an intense engram of the association of the effect of a function with that function itself, being simultaneous phenomena. Several physiologic facts are in striking accordance with it and even point to its correctness.

This same principle teaches us the cause of the chief characteristics of reflex reaction.

The reflex-tract being the path of the stimulations which are caused, actualised or altered by the future reflex-reaction, this reflex-reaction will be reflectorically evoked by a stimulus the perception of which it alters. So the reflex, according to the reflex-circle, specifically alters the relation of the animal towards the stimulus offered, i. e. it "responds" to that stimulus.

Thereby the reflex-circle augments the chance of a *useful* reaction: indifferent reactions — which do not alter the influence of the stimulus — are excluded, and so each reaction stands a chance of avoiding or opposing the so frequently detrimental influences of the outer world.

Whether the influence of the reflex-circles, which are superposed on a number of primary reflex-circles (of which the younger ones are not yet visible in neurones), brings this chance of a useful reaction to the existing height, cannot be stated yet. Probably other unknown factors are working in the same direction in consciousness. Protracted anatomical researches may perhaps reveal further rules for this superposed choice also.
